(14)

FLIGHT TEST REPORT DEPUTY FOR FLIGHT TEST (See ASDR 80-1)	2. AST NO. ASTDN FTR 68-39 ☐ PART ☒ FINAL
	3. DATE 30 October 1968
1. TEST TITLE "SKID CORRELATION STUDY" IDENT. NO. ASTE 68-5-3	4. TASK, PROJECT, OR SYSTEM NO. 921E-97356 (601)
	5. PRIORITY & AF IMPORTANCE CATEG. NO. 81P

6. OBJECTIVE AND SUMMARY

OBJECTIVE

1. The Skid Correlation Study was conducted to determine the existing correlation between runway friction levels, as measured by ground vehicles, and aircraft braking performance under various runway wetness conditions.

SUMMARY

2. The Skid Correlation Study was a joint NASA - British Ministry of Technology venture with the USAF participating. Braking tests of the F-4D and Convair 990 aircraft were conducted on the NASA Research Runway at Wallops Island, Virginia, during late 1967 and early 1968. During May and June 1968 the ground vehicle portion of the test was conducted. Representatives of the British Ministry of Technology, the NASA (National Aeronautics and Space Administration), the USAF, Federal Aviation Administration, several state agencies, and some tire and automobile manufacturers were present with their various friction measuring devices.

(Continue on separate page)

7. TEST HOURS COMPLETED	TEST HOURS SUCCESSFULLY COMPLETED	TEST HOURS REMAINING	DATA REDUCTION % COMPLETE
N/A	N/A	None	None

8. REQUESTING AGENCY: NASA

9. TEST STARTING DATE		11. TEST AIRCRAFT	21. DISTRIBUTION
1 May 1968	☐ INSTRUMENTATION ☐ INSTALLATION ☒ TEST PLANNING	N/A	ASTDN-20 12
10. TECHNICAL DOCUMENTARY REPORT TO BE ISSUED ☐ YES ☒ NO REPORT NO. (If known)		12. TEST LOCATION(S) NASA Wallops Stn, Va.	AFIAS-F3A 6
13. FLIGHT TEST PILOT N/A		OFFICE SYMBOL / EXTENSION	AFXOP-XYP 1; 3750AMAW 1; ASZO 1; TAC (OS) 1
14. DIVISION TEST ENGINEER ROBERT E. BRAEUTIGAM, 1st Lt, USAF		OFFICE SYMBOL ASTDN-20 / EXTENSION 77087	
15. INSTRUMENTATION ENGINEER N/A		OFFICE SYMBOL / EXTENSION	22. ATTACHMENTS ☐ APPENDICES ☐ TABLES ☒ FIGURES
16. PROGRAM MANAGER N/A		OFFICE SYMBOL / EXTENSION	

17. PREPARED BY	TITLE	OFFICE SYMBOL	EXTENSION
ROBERT E. BRAEUTIGAM, 1st Lt, USAF	Test Director	ASTDN-20	77087
18. CONCURRENCE (Div) N/A	TITLE	OFFICE SYMBOL	EXTENSION
19. CONCURRENCE (Div) THOMAS K. BOGAN, Lt Colonel, USAF	Chief, Flight Test Engineering Div	ASTD	73815
20. (Director) RICHARD O. RANSBOTTOM, Colonel, USAF	Director of Flight Test	AST	73125

3. Friction measurements were taken by the many different vehicles used by each participant on the various runway surfaces in dry, wet and flooded conditions. These readings were to be correlated to the actual performance of the aircraft.

4. Air Force (ASTDN-20) participation consisted of taking runway condition readings (RCR's) on the test sections of Figure 1 in dry and wetted conditions. Both a James Brake Inspection Decelerometer (JBD) and a Tapley Meter were used. The purpose here was twofold: (1) to determine the correlation of the RCR to aircraft performance, and (2) to obtain correlation between the aforementioned instruments.

5. A comprehensive report covering all phases of testing, including correlation of all ground vehicle friction measurements to aircraft performance, will be issued by NASA in November 1968.

CONCLUSIONS

6. Inasmuch as none of the runway surfaces yielded RCR's less than 18, and the aircraft exhibited poor braking performance on those surfaces, the RCR technique is not adequate for measuring braking on wet surfaces.

7. The present RCR technique is not capable of predicting the hydroplaning which may be experienced by hi-speed aircraft.

8. The RCR's did not correlate with the required stopping distance for the F-4 aircraft.

RECOMMENDATIONS

9. The following recommendation is made to Hq USAF (AFXOP) and Hq AFSC:

A high priority program should be funded by Hq USAF to examine, in detail, the accuracy of the present RCR system. Efforts should be made to improve the present system by modifying the braking procedure used. Special consideration should be given to the diagonal braking method coupled with the JBD.

10. The following procedure is recommended in lieu of pending improvements in the RCR method:

For operation on wet runways, all aircraft should assume that RCR which is designated as "WET" in the aircraft flight manual whenever the reported RCR is greater than that value. If the reported RCR is lower than the flight manual value, then the reported RCR should be used for landing roll computation.

TEST SITE

11. The test site upon which the testing was done is a section, 3450 feet long, of runway 04/22 at Wallops Station. The layout of the test section is shown in Figure 1.

12. The test runway is composed of sections of Portland cement concrete, bituminous concrete and rock asphalt. The concrete sections were finished with a canvas composition belt and a burlap belt as indicated in Figure 1. The bituminous concrete sections were of two different aggregate sizes as indicated in Figure 1. Four sections were grooved with ¼" x ¼" x 1" pitch grooves as indicated in Figure 1.

13. A rubber belt dam was installed around the runway as well as between the major test sections. This enabled flooding of each section as desired. Additional dams divided the test sections into smaller portions when a full test section was not necessary.

TEST VEHICLE

14. The test vehicle (Figure 2) used to obtain the RCR was a 1965, 9-passenger, Plymouth Station Wagon equipped with automatic transmission and standard mechanical brakes. The car was equipped with 8.25 x 14 inch tires, inflated to 30 psi.

15. The James Brake Inspection Decelerometer and the Tapley Meter were mounted side-by-side as shown in Figure 2.

PROCEDURES

16. All measurements were taken in accordance with USAF T.O. 33-1-23, "Procedure for Use of Decelerometer to Measure Runway Slickness". The station wagon entered the test section at a steady 30 mph for each run. The brakes were applied rapidly and firmly and were immediately released once the maximum readings were obtained on the instruments.

17. For wetting, the rubber belt dams were installed around the test section and the section was dampened or flooded to the desired depth by pumping water through hoses on a fire truck.

TEST RESULTS

18. The average RCR's obtained for each surface and condition are shown in Table 1.

SECTION	RCR			
	DRY	WET AND PUDDLED	FLOODED 0.2 Inch	FLOODED 0.4 Inch
A	24	22	20	20
B	26	23	22	25
C	25	23	25	24
D	25	22	20	22
E	26	22	19	20
F	24	22	22	21
G	25	24	25	24
H	26	26	27	26
I	27	23	23	23

TABLE 1. Listing of RCR's For Test Runway Sections.

19. Table 2 lists the required stopping distances (from 135 knots) for the F-4D aircraft as calculated by NASA. The stopping distance is for an aircraft weight of 36,000 lbs, with no drag chute. Test runs were made from 135 knots, or slower, across each section in each condition. The short runs for each surface and condition were matched together at corresponding speeds to get a total stopping distance for each surface in each condition.

SECTION	STOPPING DISTANCE FT. FROM 135 KNOTS		
	DRY	WET AND PUDDLED	FLOODED 0.1 to 0.3 Inch
A	3053	9011	-
B	3053	4190	
C	3053	3673	4751
D	3053	7873	9735
E	3053	5681	7006
F	3053	5321	7006
G	3053	3161	4150
	3053	3184	-
	3053	4547	-

TABLE 2. Calculated Stopping Distance for F-4D Aircraft.

20. Predicted landing rolls were obtained from the Landing Roll Charts of the Flight Manual as follows: The point corresponding to a landing roll of 3053 feet using no drag chute on a dry runway (RCR 23) was located on the chart for landing roll distance without a drag chute. This point was reflected back to the chart for landing roll distance with a drag chute. From this base point, corrections were made to the proper RCR and then again to the no-drag-chute chart to obtain the predicted landing roll. The predicted landing roll distances are presented in Table 3.

SECTION	PREDICTED LANDING ROLL			
	DRY	WET AND PUDDLED	FLOODED 0.2 Inch	FLOODED 0.4 Inch
A	3053	3900	5200	5200
B	3053	3053	3900	3053
C	3053	3053	3053	3053
D	3053	3900	5200	3900
E	3053	3900	5700	5200
F	3053	3900	3900	4500
G	3053	3053	3053	3053
H	3053	3053	3053	3053
I	3053	3053	3053	3053

TABLE 3. Predicted Stopping Distance, Taken From Flight Manual for F-4D Aircraft.

23. As can be seen in Table 1, the RCR was not markedly affected by wetness. However, the ungrooved sections (A, D, E, F and I) show a sharper drop in RCR than do the grooved ones (B, C, G, and H) in keeping with the purpose of grooving. Once wet, the ungrooved sections show further decrease in RCR. The main problem is that even when sections do have a lower RCR when wet, the RCR is still 23 or better because the dry surfaces had RCR's as high as 27. As a result, some sections show no change in stopping distance even though there was some decrease in RCR.

24. The RCR did not respond well to flooding. The change from a 0.2 inch flooded condition to a 0.4 inch flooded condition had little or no effect on RCR. In some cases the increased flooding caused the RCR to increase.

25. Correlation of the RCR and predicted stopping distance to calculated stopping distance was not good. Increases in calculated stopping distance of up to 55% were obtained with no increase in predicted landing roll. The RCR did decrease in these cases but never below 23. On surfaces which produced calculated stopping distance increases greater than 55% the RCR does predict increased stopping distance. However, the disparity between the predicted and calculated stopping distances become obvious in comparing Tables 2 and 3. The predicted stopping distances range from only 43% to 81% of the calculated stopping distances. For all surfaces the required landing distance ranged from 4% to 240% greater than the RCR indicated.

26. In order to predict the landing distances experienced, RCR's as low as 11 or 12 would have been necessary for the longest distances and 14 or 15 for the others. Even an RCR of 14, the value designated as "WET" in the flight manual, would not forecast the 9011 and 9735 feet landing distances required for wet and flooded concrete sections A and D.

27. In order to obtain low RCR's the station wagon was tested on another site which was covered with JENNITE. This surface was exceptionally slick when wet. The following RCR's were obtained.

Grooved........12

Ungrooved......10

No aircraft data are available for this surface since it was not located on the test runway. However, it does serve as an example to indicate that low RCR's were obtainable on sufficiently slick surfaces.

28. Runs were also made by two FAA station wagons. The RCR's obtained in these vehicles are presented below.

SURFACE	RCR	
	WET AND PUDDLED	FLOODED
A	20	19
B	20	21
C	-	22
D	20	18
E	18	18
F	-	-
G	-	21
H	-	22
I	-	19

TABLE 5. RCR's Obtained by FAA Vehicles.

29. The predicted stopping distances for the F-4D are then as follows:

SURFACE	STOPPING DISTANCE (FT.)	
	WET AND PUDDLED	FLOODED
A	5200	5700
B	5200	4500
C	--	3900
D	5200	6050
E	6050	6050
F	--	-
G	--	4500
H	--	3900
I	--	5700

TABLE 6. Predicted Stopping Distances for F-4D Aircraft Based on FAA RCR's.

30. The RCR's obtained by the FAA vehicles are generally lower and the predicted stopping distance correspondingly longer than those obtained by the USAF vehicle. This could be due to two prime factors: (1) operator technique, and (2) the make of vehicle used. A consistent difference in RCR was noticeable between the two vehicles used by the FAA. The difference in suspension between two makes of automobiles produces different amounts of "dip" upon braking. Driver technique in brake application has always been recognized as a variable factor in the RCR produced.

31. It is of importance to note that the RCR's obtained were never less than 18; still far from the 11 or 12 that is necessary to predict a stopping distance of 9000 feet for the F-4D aircraft. Moreover, the RCR's do not reflect the increases in calculated stopping distances for the F-4 aircraft. For example: Sections A, B, and D produced the same RCR (20) in the "Wet and Puddled" condition calling for a predicted landing roll of 5200 feet. The calculated landing rolls were 9011, 4190, and 7873 feet respectively, a considerable disagreement. In addition, surface E had a lower RCR (18) for the "Wet and Puddled" condition, predicting a landing roll of 6050 feet. However, the calculated stopping distance for the F-4 aircraft on this surface was 5631 feet. The disagreement is obvious; the RCR was lower for section E than for sections A and D, yet the calculated stopping distance was lower.

32. For reasons of comparison, the readings from the Tapley Meter are presented as RCR's in Table 7. As an automobile is decelerated the deceleration is as follows: $a = \mu g$. Where a = deceleration in feet per second per second, μ = coefficient of friction and g = acceleration due to gravity. An accelerometer which senses the deceleration then can also indicate μ. The Tapley Meter indicates μ from 0 to 1.00. Likewise the JBD can be read in terms of: (1) μ on the "percent grade" scale, and (2) RCR. The RCR is not equivalent to a deceleration in feet per second per second. (e.g., An RCR of 16 is not a deceleration of 16 feet per second per second and is not produced at 0.5g). It is possible, however, to interpret Tapley readings as RCR's by reading the RCR on the JBD dial corresponding to the Tapley μ value on the "percent grade" scale. Examination of Table 7 shows the similarity of performance. The Tapley Meter reads consistently lower, a feature of the oil damping in this instrument versus air damping in the JBD. Most important, these values illustrate the fact that it is not solely any one instrument which causes the poor correlation, but rather the method of obtaining the RCR. Both instruments registered an increase in braking on surfaces which actually caused poorer aircraft braking as mentioned in paragraph 31. Generally, the instruments indicated better braking on a surface than what the aircraft actually experienced in tests.

SURFACE	TAPLEY READING CONVERTED TO RCR			
	DRY	DAMP	FLOODED 0.2 Inch	FLOODED 0.4 Inch
A	21	20	18	18
B	23	20	20	24
C	21	20	23	21
D	21	19	17	19
E	24	20	18	19
F	21	21	21	20
G	20	22	23	22
H	22	24	24	24
I	21	22	21	21

TABLE 7. Tapley Readings Expressed as RCR.

33. It is felt that the poor correlation of RCR to aircraft performance is due not to the JBD itself, but rather to the method in which the RCR is obtained.

34. The tests conducted here were not of sufficient number to isolate the combined effect of driver technique and type vehicle used so these effects must be discounted. It is recognized that the driver technique and vehicle used do affect the RCR but the extent cannot be specifically stated here.

35. The physical variables in braking in relation to aircraft/ground vehicle correlation will be discussed by NASA in its final report on this study and at the Pavement Grooving and Traction Studies Conference that NASA is convening in November 1968. Due to the volume of data obtained, which is available to NASA personnel, their report and conference will contain a more comprehensive discussion of the entire correlation problem.

36. The original intention when the RCR system was introduced was not to reproduce actual aircraft braking (which seems impossible), but to correlate aircraft performance and vehicle performance. The possible explanations for failure to do so are:

a. HYDROPLANING: Using the relation $V_H = 10.35\sqrt{P}$ (V_H = Hydroplaning Speed, mph, P = Tire pressure in psi), it is found that the dynamic hydroplaning speed for an automobile with tires inflated to 30 psi is 58 mph. The RCR's are obtained at 30 mph - well below the hydroplaning speed. The aircraft, however, touches down at a speed at or near its hydroplaning speed so it will be subject to hydroplaning which the RCR method is not designed to detect. Also important is viscous hydroplaning. The grooved tread design of the automobile tire does much to reduce this factor producing higher coefficients of friction than do smooth-treaded or bald tires. Generally, the smooth treads of aircraft tires are more subject to viscous hydroplaning than are the automobile tires used on either the test vehicle here or on most automobiles in general.

b. SPEED: This factor ties in closely with all factors affecting braking. As speed increases the coefficient of friction decreases. However, the coefficient of friction decreases more with speed for wet surfaces than it does for dry surfaces. This is because speed enhances the viscous and dynamic hydroplaning aforementioned. Dry coefficients of friction remain nearly the same at all speeds but the wet coefficients decrease markedly at high speeds. Examination of friction data from several vehicles used during the Wallops test has shown that the variation of coefficient of friction from dry to wet to flooded conditions is generally slight at 30 mph but marked at speeds of 60 mph.

c. TIRE TREAD DESIGN: Design of the tire tread has a significant effect on braking, especially for wet surfaces. Tests conducted by tire manufacturers have shown that tread design introduces a variability factor as much as 8:1 when compared to a bald tire. Tire grooving and siping do much to reduce the hydroplaning problems and increase the coefficients of friction on wet surfaces. However, the variability due to tread design, tread depth, etc., can overshadow the variability due to surface condition.

CONCLUDING REMARKS

37. It appears that the braking experienced by a station wagon equipped with new (or unworn), standard automobile tires at the low speed of 30 mph is still so high on wet surfaces that it is not accurate enough to predict aircraft performance. It certainly is not accurate enough for the operational commands of the USAF and Civil Airport operators under regulation of the FAA.

38. The following tentative solutions are offered in view of the discussion in paragraph 36.

a. Firstly, it would be advisable to increase the speeds at which RCR's are taken to say 60 mph. At this speed, greater variance in performance would be experienced.

b. Secondly, the use of completely bald tires would eliminate the tread effects and, at the same time, reduce coefficients of friction to realistically representative values.

39. In order to offset the control problems incurred by the high speed/bald tire combination, diagonal braking could be used. This method would involve only braking the right front and left rear wheels (by means of brake line modification) to leave the other wheels free-rolling for control. NASA personnel have tested this combination at Wallops Island and have obtained satisfactory correlation of RCR and aircraft performance.

TEST SURFACES

* Smooth concrete surface finished with a canvas composition belt
** Standard concrete surface finished with a burlap belt
\+ Smooth bituminous concrete surface-aggregate ≤ 3/8 inches
\+\+ Standard bituminous concrete surface-aggregate ≤ 3/4 inches

<u>Note</u>: Groove dimensions are $\frac{1}{4}'' \times \frac{1}{4}'' \times 1''$ pitch.
Dams internal to test section have been omitted.

B, C, G, and H are grooved.

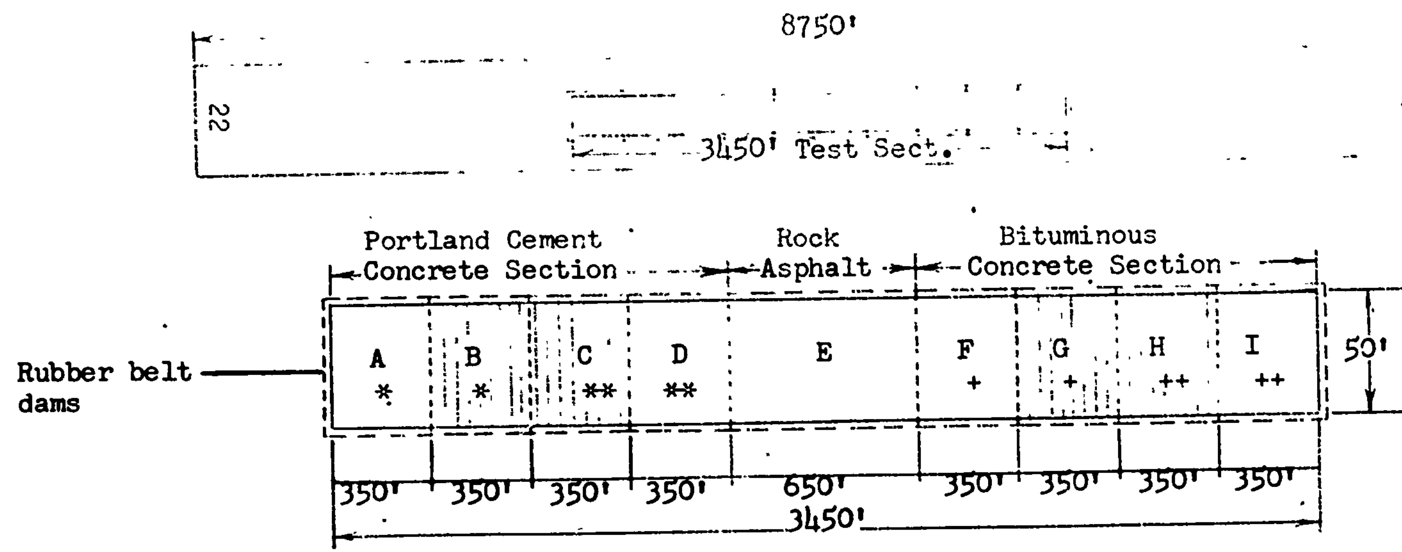

Figure 1: Test runway arrangement and description.